Survey of Magnetic Materials and Applications in the Telephone System

By V. E. LEGG

The great diversity of magnetic characteristics demanded by telephone apparatus, and the large number of available magnetic materials propose intricate problems in the choice of materials and design of apparatus to attain greatest efficiency and economy. The present paper undertakes to evaluate magnetic materials in relation to apparatus needs. After a review of the earlier developments, the materials now available are listed, together with data on technical characteristics and raw materials costs. The advantages of various materials for specific applications are described. The scope of possible further improvements in magnetic materials is surveyed.

Historical

TWENTY years ago, the telephone system used primarily iron, together with a small amount of silicon iron, for applications requiring soft magnetic materials, and carbon, tungsten or chromium steel for permanent magnet applications. The permalloys [1] were already fairly thoroughly developed by 1920 in what is now the Bell Telephone Laboratories, and 78.5 permalloy [2] shortly attained commercial recognition for its utility as a continuous loading material for submarine telegraph cables.[3] This and other nickel-iron alloys were soon serving in many types of telephone relays, and in various coils where the designs could be profitably modified to adapt them to the new materials. Upon the development of commercial means for embrittling and pulverizing permalloy, this material was soon in extensive use because it offered improved characteristics over the compressed powdered iron core material previously in use. Redesigns of filter and loading coils have introduced such economies that practically all these coils made by the Western Electric Company have until recently employed compressed powdered permalloy cores.[4]

A desire to reduce the losses in a-c. apparatus arising from eddy currents in magnetic parts led to the development of permalloys of higher

[1] H. D. Arnold & G. W. Elmen, *Jour. Frank. Inst. 195*, 621 (1923).
[2] The approximate chemical compositions of the various materials herein discussed are given in Tables I and II.
[3] O. E. Buckley, *Jour. A. I. E. E. 44*, 821 (1925).
[4] W. J. Shackelton & I. G. Barber, *Trans. A. I. E. E. 47*, 429 (1928).

resistivity, containing several per cent chromium or molybdenum.[5] The problems of embrittlement and pulverization of molybdenum permalloy were also successfully solved. This material has been recently adopted for manufacture of filter and loading coil cores,[6] in which material of higher resistivity is especially advantageous.

Attempts to decrease the losses due to hysteresis led to the discovery of the nickel-iron-cobalt alloys—the perminvars. A molybdenum-perminvar was perfected for use in the continuous loading of submarine telephone cable.[7]

The large economic advantages promised by improvements in soft magnetic materials confined much of the earlier work to this field. However, within the last 20 years new permanent magnet materials have been discovered here and abroad which offered radical improvements in this direction. Such materials have been introduced in telephone apparatus wherever found advantageous.

Characteristics of Available Materials

The number of different magnetic materials in use is quite large on account of the various combinations of properties required for special applications and on account of a multiplicity of trade names. For the present purpose, an abbreviated listing is given of typical materials covering the whole range of magnetic properties, particularly those of interest to the telephone system. A compilation of representative data is given in Tables I and II.

The fundamental property which distinguishes a ferromagnetic material is that when it is subjected to a magnetic field it develops magnetic flux considerably larger than similarly attained in air. The magnetizing forces of interest in telephone apparatus range from less than 10^{-3} to upwards of 10^3 oersteds, and the flux densities from less than 1 to 30,000 gausses or more. The relation of flux density B to magnetizing force H for important materials as first magnetized is given on a logarithmic scale in Fig. 1. The ratio of B to H is the permeability, which can be read on the diagonal scale [8] in the figure. It is evident that the initial permeability μ_0 and the maximum permeability μ_m vary over a wide range from the hard magnet steels to the softest magnetic alloys. For commercial materials, 4–79 Mo-permalloy gives the largest initial permeability—around 22,000, and 78.5 permalloy gives the largest maximum permeability—about 105,000.

[5] G. W. Elmen, *Jour. Frank. Inst. 207*, 583 (1929).
[6] O. E. Buckley, *Jour. Applied Phys. 8*, 40 (1937).
[7] G. W. Elmen, *Elec. Engg. 54*, 1292 (1935).
[8] Scale due to Aiken; *Jour. Applied Phys. 8*, 470 (1937).

TABLE I

Soft Magnetic Materials in Solid or Sheet Form

Per Cent Composition						Raw Cost ¢/lb.	Typical Anneal	Material	Initial Permeability	Maximum Permeability	Saturation	Hysteresis Loss at Saturation	Residual	Coercive Force	Resistivity	Curie Temperature	Hysteresis Coefficient	Density
Other	Mn	Mo	Ni	Co	Fe				μ_0	μ_m	$4\pi I_\infty$	W_∞	B_r	H_c	ρ	θ	$a \times 10^6$	σ
											gauss	*erg/cm.*[3]	*gauss*	*oersted*	*microhm-centimeter*			*gm./cm.*[3]
3 C, 2 Si					95	<1	800° (Centigrade)	Cast Iron	—	600	—	20,000	5,300	4.6	30	—	—	—
					99.94	7*	900° Pot	Magnetic Iron	250	5,500	21,500	5,000	13,000	1.0	10	770° C.	50	7.88
					99.98	7	1480° H_2+880° H_2	Magnetic Iron H_2 Purified	25,000	275,000	21,500	300	13,600	0.05	10	770	—	7.88
0.5 Si					99.5	7*	800° Pot	0.5 Si-Iron (Field)	250	3,700	21,000	4,500	12,800	0.8	18	760	—	7.7
4 Si					96	8*	800° Pot	4 Si-Iron (Transformer)	400	6,700	20,000	3,500	12,000	0.5	60	690	120	7.5
9½ Si, 5½ Al					85	3	Cast	Sendust	30,000	120,000	10,000	100	5,000	0.05	80	—	—	7.1
0.2 Cu			99.0		0.4	35	1000° Pot	Nickel	110	600	6,100	3,000	3,600	3.4	8	360	100	8.85
	0.6		45		54.4	17	1100° Pot	45 Permalloy	2,700	23,000	16,500	1,200	8,000	0.3	45	440	0.4	8.17
			50		50	18	Long 1200° H_2	Hipernik	3,000	70,000	16,500	220	7,300	0.04	35	500	—	8.25
	0.6		78.5		20.9	28	1000° +Quench	78.5 Permalloy	9,000	105,000	10,700	200	6,000	0.05	16	580	0.2	8.60
5 Cu	1.0		74		20	27	900° +Quench	Mumetal	7,000	80,000	8,500	200	6,000	0.05	25	—	—	8.58
3.8 Cr	0.6		78.5		17.1	29	1000° Pot	3.8–78.5 Cr-Permalloy	10,000	40,000	8,000	200	4,500	0.05	65	455	0.3	8.56
	0.6	4	79		16.4	32	1000° Pot	4–79 Mo-Permalloy	22,000	72,000	8,500	200	5,000	0.05	55	460	0.05	8.72
15 Cu	1.0	3	71		10	29	1100° H_2	1040 Alloy	40,000	100,000	6,000	200	2,500	0.014	55	290	—	8.76
		12.5	80		7.5	40	800° H_2	12.5–80 Mo-Permalloy	9,000→1, over room temperature range					—	—	40	—	8.9
				99		136	1000° Pot	Cobalt	70	240	18,000	2,000	5,000	10	9	1120	30	8.9
				50	50	69	900° Pot	Permendur	800	5,000	24,500	12,000	14,000	2.0	7	1000	—	8.3
2 V				49	49	73	800° Pot	2 V-Permendur	800	4,500	24,000	6,000	14,000	2.0	26	980	1.0	8.2
	0.6		45	25	29.4	50	1000° +425° Bake	45–25 Perminvar	365	1,800	15,500	4,000	3,300	1.4	19	715	0.01	8.6
	0.6		70	7	22.4	35	1000° +425° Bake	7–70 Perminvar	850	4,000	12,500	—	2,400	0.6	16	650	0.06	8.6
	0.6	7.5	45	25	21.9	57	1000° +425° Bake	7.5–45–25 Mo-Perminvar	550	3,800	10,300	2,600	4,300	0.6	80	540	0.1	8.66

* Approximate finished cost for 14 mil sheet.

Note: Values for μ_0, μ_m, W_∞, B_r, H_c and a are subject to considerable variations, depending on purity of materials, composition, type of heat treatment, and final condition of mechanical stress.

TABLE II

PERMANENT MAGNET STEELS

Per Cent Composition					Raw Cost ¢/lb.	Typical Heat Treatment		Material	Initial Permeability	Reversible Permeability	Saturation	Residual	Coercive Force	Energy Product	B for (B·H) = Maximum	Resistivity	Curie Temperature	Density
Other	Cr	Ni	Co	Fe		Quench	Aging		μ_0	μ_r	$4\pi I_\infty$	B_r	H_c	$(B\cdot H)_{max.}$		ρ	θ	σ
											gauss	*gauss*	*oersted*		*gauss*	*microhm-centimeter*		*gm./cm.*^{3}
0.6 C, 0.8 Mn				98.8	0.8	800° C. Water	—	Manganese	75	—	21.000	10,000	50	0.2×10^6	6,900	20	750° C.	7.8
0.6 C, 0.4 Mn	1			98	0.9	800° Oil	—	1% Chrome	—	—	—	9,800	50	0.2	6,900	—	—	—
1 C. 0.4 Mn	3			96	1.1	840° Oil	—	3% Chrome	—	31	—	9,700	65	0.3	6.100	38	—	7.7
5 W, 1 C				94	9	840° H_2O	—	5% Tungsten	—	32	—	10,800	60	0.3	7,000	30	—	8.0
7 W, 0.5 Mn	3.5		36	52	62	940° Oil	—	Cobalt (Honda KS)	7	9.4	19,000	9,500	220	0.9	6,000	27	700	8.3
6.7 Ti, 3.7 Al		18	27	45	53	Cast	650°	Honda, New	3	3.8	—	7,100	780	2.0	4,100	65	—	7.3
13 Al		29		58	14	1200° Oil	600°	Mishima	4	5	11,600	6.000	550	1.4	3,500	60	750	7.1
14 Al		25		60	12	1200° Oil	600°	Oerstit 500	—	5	—	6,500	500	1.4	4.400	60	—	—
12 Al		20	5	63	17	1200° Oil	600°	Alnico I	—	4	—	7,300	430	1.4	4,500	60	—	7.0
10 Al. 6 Cu		17	12.5	54.5	26	1200° Oil	600°	Alnico II	—	4	—	7,200	540	1.6	4,400	—	—	7.1
17 Mo			12	71	33	1300° Oil	700°	Remalloy	8	12	17,000	10,500	250	1.1	6,500	45	780	8.4
60 Cu		20		20	13	1000° Oil	600°	Magnetoflex[9]	3	3	5,000	3,400	390	0.5	1,800	—	—	—
41 Cu		24	35		60	1050° Oil	600°	Magnetoflex[10]	4	4	8,600	5,300	440	1.0	3,400	38	850	8.7
77 Pt			23		$400	1200° Oil		77 Platinum—Cobalt	1.1	1.1	—	4.500	2,600	3.8	2,500	50	—	—
2 Fe_2O_3+1 Fe_3O_4 +1 Co_2O_3					25¢	950° Vacuum+Magnetize at 500°		Oxide, Compressed	1.7	1.7	—	1,800	600	—	—	10^{12}	350	3.8

[9] Neumann, Bücher & Reinboth, *Z. f. Metallkunde 29*, 173 (1937).
[10] Dannöhl & Neumann, *Zeit. f. Metallkunde 30*, 217 (1938).

Note: Values for μ_0, μ_r, B_r, H_c and $(B\cdot H)_{max.}$ are subject to considerable variations, depending on purity of materials, composition, and heat treatment.

TABLE III

Curve Number	Material	Typical Heat Treatment (Temperature in Degrees C.)	Initial Permeability	Maximum Permeability	Saturation	Hysteresis Loss at Saturation	Residual	Coercive Force	Resistivity
			μ_0	μ_m	$4\pi I_\infty$	W_∞	B_r	H_c	ρ
					gauss	*erg/cm.*^{3}	*gauss*	*oersted*	*micro-ohm-cm.*
	Soft Magnetic Materials								
1	Magnetic Iron	900 Anneal	250	5,500	21,500	5,000	13,000	1.0	10
2	4 Per Cent Silicon Iron	800 Anneal	400	6,700	20,000	3,500	12,000	0.5	60
3	45 Permalloy (Ni, Fe)	1100 Anneal	2,700	23,000	16,500	1,200	8,000	0.3	45
4	78.5 Permalloy (Ni, Fe)	1000 + Air Quench	9,000	105,000	10,700	200	6,000	0.05	16
5	4–79 Mo-Permalloy (Mo, Ni, Fe)	1000 Anneal	22,000	72,000	8,500	200	5,000	0.05	55
6	2 V Permendur (V, Co, Fe)	800 Anneal	800	4,500	24,000	6,000	14,000	2.0	26
7	45–25 Perminvar (Co, Ni, Fe)	1000 + 425 Bake	365	1,800	15,500	4,000	3,300	1.4	19
	Magnet Steels					Energy Product $(B\cdot H)_m$ $\times 10^{-6}$			
8	3 Per Cent Chrome	840 Quench	10	100	—	0.34	9,700	65	38
9	Honda (C, W, Co, Fe)	940 Quench	7	—	19,000	0.9	9,500	220	27
10	Mishima (Al, Ni, Fe)	Quench + 600 Bake	4	16	11,600	1.4	6,000	550	60
11	Remalloy (Mo, Co, Fe)	Quench + 700 Bake	12	30	—	1.1	10,500	250	45
12	Oxide (Fe, Co, O_2)	950 Vacuum	1.7	—	—	—	1,800	600	10^{12}

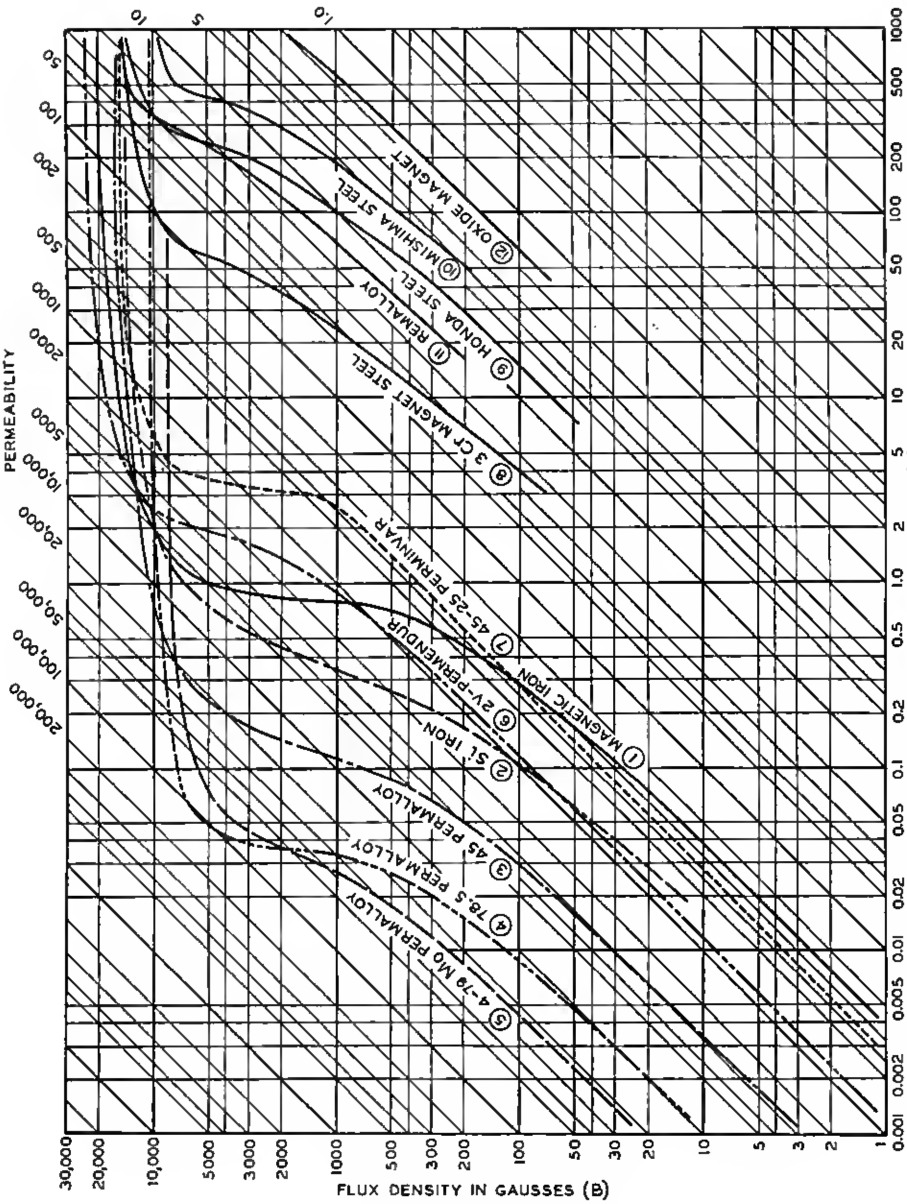

Fig. 1—Magnetization and permeability curves for important magnetic materials (diagonal scale for permeability values).

The saturation flux density for the soft magnetic materials can be read from these curves, and it is listed in the adjacent Table III in the column headed $4\pi I_\infty$. The pre-eminence of 2 V-permendur is noteworthy.

Further important magnetic properties are obtained from the hysteresis loop. This gives the B, H relationship for a material which has already been magnetized up to a peak value H_m. The flux density remaining after the removal of a very large magnetizing force is the residual B_r, and the reverse magnetizing force necessary to bring the flux to zero is the coercive force H_c. The area of the B, H loop when the peak magnetizing force is very large gives the maximum energy W_∞ dissipated by hysteresis in the material when it is carried from positive magnetic saturation to negative, and back again. Table III gives values of W_∞, B_r and H_c. The low values of these properties for 4–79 Mo-permalloy are noteworthy. Among soft magnetic materials, iron and 2 V-permendur have high residual and coercive force, properties which are occasionally useful.

Permanent magnet materials should have large values of B_r and H_c, although a sacrifice of residual can be more or less compensated by an increase in coercive force. A more fundamental criterion of permanent magnet quality is the peak energy product $(B \cdot H)_{\max.}$ obtained from the demagnetizing section of the hysteresis loop.[11] Values of this product are given for several magnet steels in Table III. Mishima steel is seen to be foremost in this regard, with remalloy nearly as good.

The last column in Table III gives the resistivity ρ of each material. A high resistivity such as obtained with molybdenum additions to permalloy and perminvar is desirable in suppressing eddy current losses for alternating current applications. Eddy current losses can also be suppressed by proper subdivision of the material, but this method becomes costly with fine subdivision.

For apparatus depending upon the tractive force of a magnet, the high flux density properties of materials are most important. Since these do not show up clearly in Fig. 1, an accompanying Fig. 2 has been prepared in which the $(B - H)$ scale is quadratic, and thus proportional to tractive force. The relative merits of various materials for such applications are seen by inspection of these curves. 2 V-permendur is outstanding at high flux densities, iron and 45 permalloy at intermediate, and 4–79 Mo-permalloy at low flux densities.

The use of a purifying hydrogen anneal has been shown by Cioffi [12] to increase the ease of saturating iron and most magnetic alloys. The

[11] S. Evershed, *J. I. E. E.*, London, *58*, 780 (1920); *63*, 725 (1925).
[12] P. P. Cioffi, *Phys. Rev. 39*, 363 (1932).

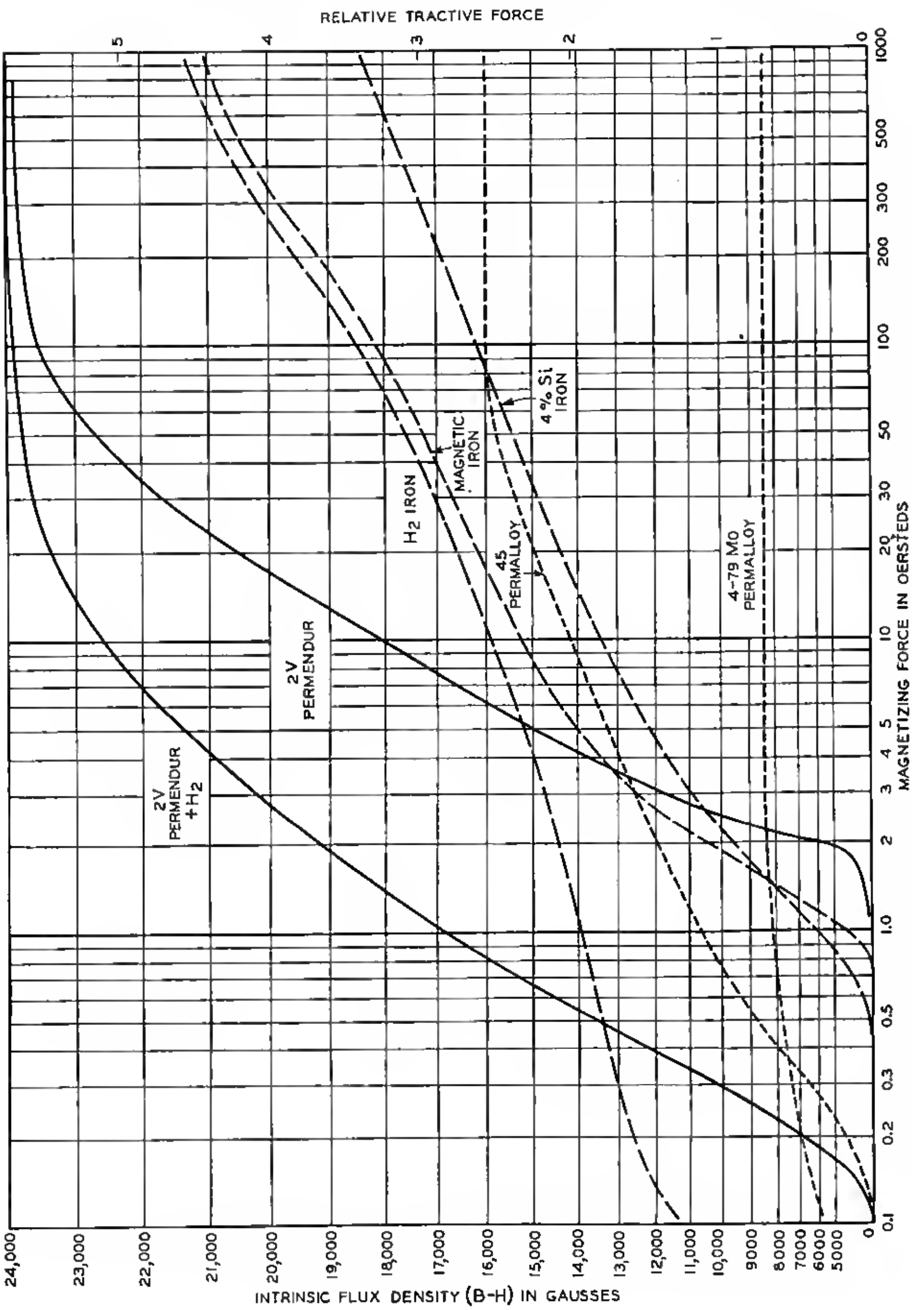

Fig. 2—Magnetization curves plotted to show the relative tractive force for important magnetic materials.

in the direction of rolling[19] (see Table IV). Such materials have been used to some extent abroad for loading coil cores. Aside from the difficulty of attaining as low hysteresis loss, high permeability, and high stability as obtainable with permalloy powder cores, such materials appear to be at an economic disadvantage because of the high cost of rolling sheet thin enough for eddy current loss reduction.

Stresses well within the elastic limit increase or decrease the permeability of materials, depending on the composition.[20] Furthermore, tension and compression generally have opposite effects. The changes in permeability due to such weak stresses are not permanent, but practically disappear when the stress is removed.

Cost of Magnetic Materials

Many materials having very desirable technical qualifications cannot be used extensively because of their high costs. Thus, nickel at 35¢/lb., cobalt at \$1.35/lb., tungsten at \$1.80/lb., and vanadium at

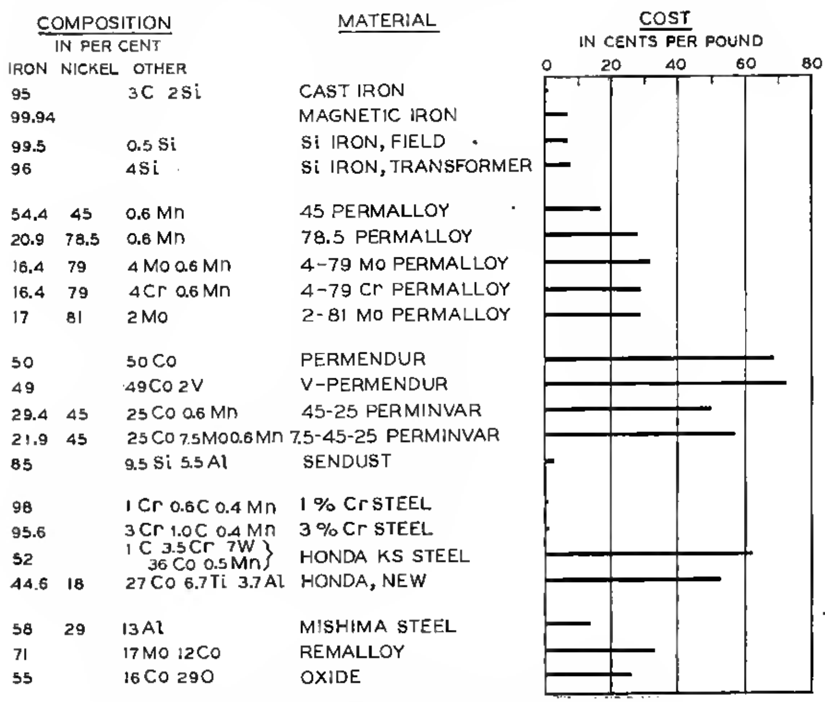

Fig. 3—Raw materials cost of various magnetic alloys.

[19] O. v. Auwers, *Wiss. Ver. a.d. Siemens-Werk. 15*, 112 (1936).
[20] O. E. Buckley & L. W. McKeehan, *Phys. Rev. 26*, 261 (1925).

\$2.80/lb. increase the cost of an alloy very considerably in comparison with iron or steel at less than 7¢/lb. High priced magnetic alloys can only be justified in general when their extraordinary characteristics permit offsetting apparatus performance or economies. Of course, they may be absolutely necessary for certain types of apparatus.

The cost data for Tables I and II have been calculated from recent prices[21] for raw materials of quality suitable for magnetic alloys. The cost of raw materials is given in Fig. 3 for selected alloys. The low raw materials costs of iron, silicon-iron, and chromium steel are notable, as well as that of the powder core material "Sendust." 45 permalloy is the cheapest of the high permeability materials, while Mishima steel is the cheapest of the high quality permanent magnet materials.

Comparisons based on raw materials costs are not entirely satisfactory. The cost of alloying and reducing to finished form may overshadow the cost of raw materials, particularly when high purity, exact tolerances, and small rates of production are involved.

Applications

Almost all magnetic properties are utilized in some type of telephone apparatus. They are generally linked inseparably with electrical and mechanical properties. The proper design of any apparatus strikes a compromise between the various technical features and cost. The technical features of materials used in present day apparatus are listed below. Acceptable common properties, such as mechanical soundness and workability, are assumed for all materials unless specifically mentioned. Listing is made on the basis of the magnetic effect utilized.

1. *Simple Tractive Force* (*Relays*)

The force of attraction between two neighboring surfaces of area A, between which the flux density is B, is

$$F = kAB^2.$$

The primary telephone application of this effect is to relays and switches. For greatest tractive force, materials capable of attaining high flux densities are desirable. However, the air gap in the magnetic circuit absorbs such a large proportion of the available magnetomotive force that higher or lower permeabilities in the core material are frequently less important than efficiency of design. A typical relay structure is shown in Fig. 4.

[21] *Steel*, Oct. 3, 1938.

Reference to Figs. 1 and 2 points to 2 V-permendur as outstanding in the flux density range above 15,000 gausses. This material is excluded for many applications because of its high cost. High temperature hydrogen annealing improves the high flux density behavior of most magnetic materials, as noted above in connection with Fig. 2. Using ordinary methods of annealing, the next best material for high flux operation is the standard magnetic iron, while 45 permalloy is preferable at flux densities below 12,000. For the low magnetizing forces available in sensitive relays, 4–79 Mo-permalloy gives the largest tractive forces.

There are frequently other requirements in addition to tractive force in relay construction. The operation and release characteristics

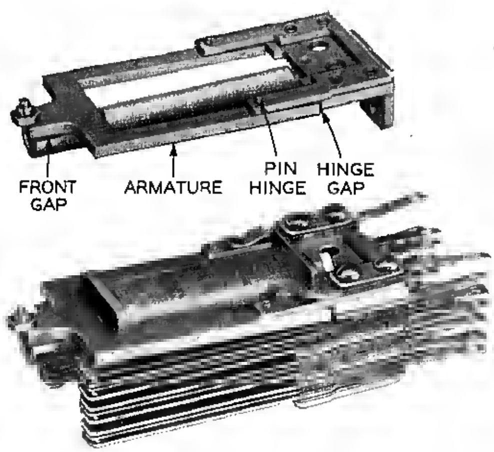

Fig. 4—U-type relay, showing the magnetic circuit

are determined by the resistivity and coercive force of the material. Sensitive, quick release relays require materials like permalloy, while slow release types may utilize the larger coercive force and residual of magnetic iron or cold rolled steel.[22, 23]

Relays for a-c. applications may have objectionable eddy current losses in their cores. Such losses can be reduced by use of high resistivity material. Thus, 45 permalloy has one-fourth the loss of iron for the same core thickness and flux density.

2. *Polarized Tractive Force* (*Receivers*, *Ringers*, *Relays*)

If permanent polarizing flux density B_p exists between two neighboring surfaces, and a small additional flux Φ is applied by means of a

[22] H. N. Wagar, *Bell Labs. Record 16*, 300 (1938).
[23] F. A. Zupa, *Bell Labs. Record 16*, 310 (1938).

magnetomotive force M, the additional tractive force will be approximately

$$F = 2kB_p\Phi = \frac{2kB_pM}{R_a(1 + n/\mu_r)},$$

where R_a in the latter part of the above equation is the reluctance of the air-gap, n is ratio of the reluctance of the ferromagnetic circuit with iron removed to the reluctance of the air-gap, and μ_r is the reversible permeability, i.e. the permeability measured with very small a-c. magnetizing forces in the presence of the polarizing flux density. It thus appears that materials for such applications should have high saturation values. The apparatus should be designed to obtain a low value of n, and to operate at a flux density to make the above force a maximum.

Figure 5 gives values of μ_r as a function of polarizing or superposed flux density B_p. It should be remarked that the reversible permeability is practically single valued [24] when plotted against polarizing flux, in contrast with the "butterfly" loop obtained by plotting against polarizing field strength. The superiority of permendur in Fig. 5 is obvious. Values of the force factor for $n = 100$ and $n = 1000$ have been computed for these materials for an arbitrary value of air-gap reluctance and magnetomotive force. It is evident that the full advantage of permendur is not realized unless the apparatus design is such as to attain a low value of the air reluctance ratio n.

Permanent magnet materials are frequently employed to supply polarizing flux. When they form a part of the circuit for the alternating flux, their reversible permeability becomes important. Reference to Table II shows that 5 per cent W steel has the highest permeability of the common permanent magnet materials. However, its energy product $(B \cdot H)_{max}$ is so low that other materials are preferred for applications where space is limited, despite their low reversible permeabilities.

The earliest application of polarized structures in the telephone plant was to the receiver. The receiver of the present day is constructed with remalloy permanent magnets, 45 permalloy pole-pieces, and a permendur diaphragm.[25] The magnetic circuit is shown in Fig. 6.

The second application of polarized structures is to the telephone bell or ringer. Here a permanent magnet is used, to supply polarizing flux to the two cores for the coils through the shoe at one end and the

[24] R. Gans, *Phys. Zeit. 12*, 1053 (1911).
[25] W. C. Jones, *B. S. T. J. 17*, 338 (1938).

armature at the other.[26] Non-magnetic stop pins are required on the armature to prevent sticking. This complicated magnetic circuit has been developed to meet the numerous requirements placed on ringers. Polarization is necessary for an a-c. ringer which is to operate without

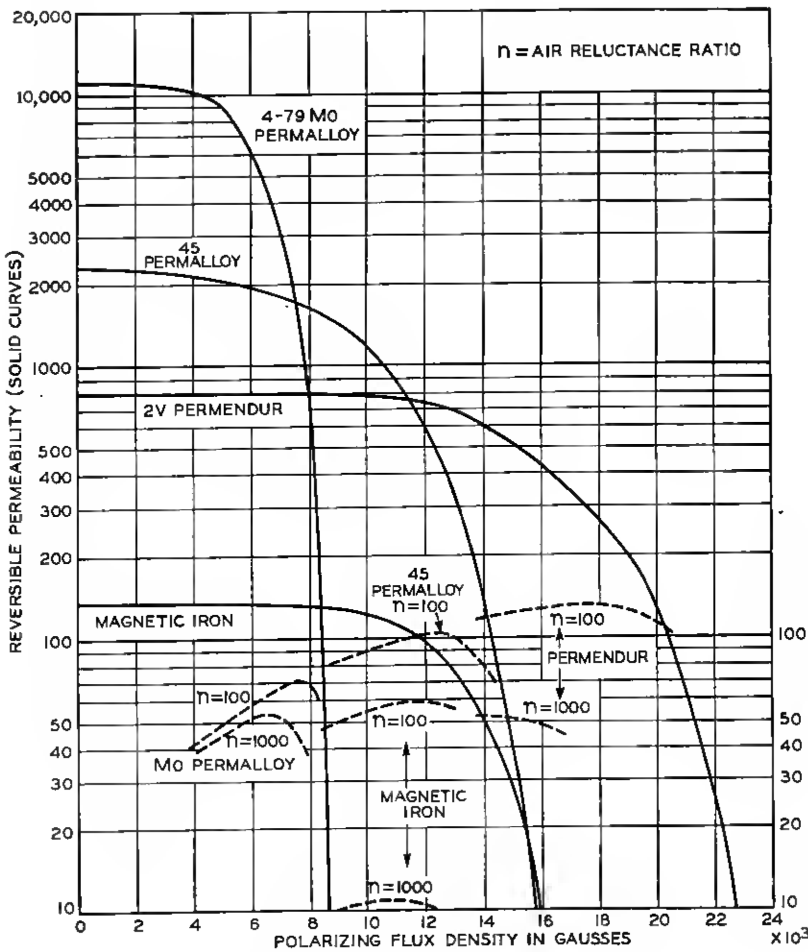

Fig. 5—Reversible permeability and relative polarized tractive force for various magnetic alloys.

interrupter contacts, and it is employed in selective ringing on party lines. A high coil inductance is required to limit the transmission

[26] K. B. Miller, "Manual Switching and Substation Equipment" (McGraw-Hill, 1933 ed.), p. 67.

losses due to the shunting effect of ringers across the line, especially in the case of party lines.

The third application of polarized structures is in certain relays for composite ringing, duplex telegraph, and special selecting circuits. Various materials are used in such relays, depending upon the sensitivity required, so that no general statement can be made as to needs in this field. The problems encountered are essentially similar to those met in the receiver and ringer, for which numerous materials are available.

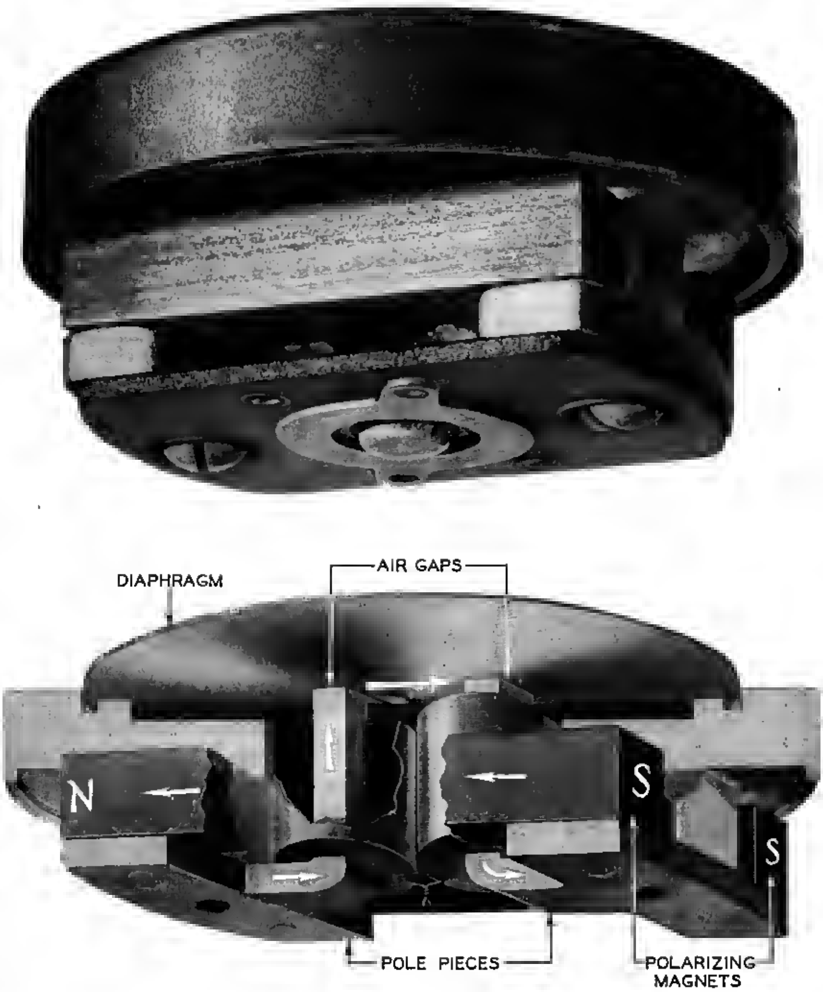

Fig. 6—Magnetic circuit of the new telephone receiver.

3. *Force on Current (Moving Coil Receivers, Light Valves, Motors)*

A straight wire of length l carrying a current i in a perpendicular magnetic field of flux density B is pushed at right angles to the field and the length with a force

$$F = Bil = \mu Hil,$$

where μ is the permeability and H is the magnetizing force in the nearby material from which the flux is derived. Again, the prime requirement for a useful material is high flux capacity, and high permeability, so that the magnetizing force need not be large. The magnetizing force has been supplied generally in the past by means of direct current in windings built into the apparatus. With the normally available voltages and currents, sufficient magnetizing forces could be obtained only with coils having a large number of turns, and low resistance. This generally involved such large structures that cost considerations compelled the use of iron cores with perhaps pole-pieces made of permendur. Lately many structures are being designed to replace costly electromagnets with permanent magnets made from Mishima type steel.

Moving coil receivers and loud speakers [27] are the most important representatives of this type of apparatus. Others are the string oscillograph,[28] the light valve,[29] phonograph record recorder,[30] and various types of power machinery.[31] Several of these are now constructed with permendur pole-pieces, and cast Mishima steel magnets, or remalloy magnets where hot rolling will assist in producing small, accurately sized parts.

4. *Induced Electromotive Force*

The electromotive force between the terminals of a coil of N turns linking flux φ is

$$-e = N\frac{d\varphi}{dt}.$$

The arrangement of coils and interlinking flux differs considerably in the various types of apparatus employing this effect.

The flux variation is provided by means of mechanical motion of the coil in instruments such as the electromagnetic microphone. It is varied by means of fluctuations in magnetizing current in inductance

[27] E. C. Wente & A. L. Thuras, *B. S. T. J. 10*, 565 (1931).
[28] A. M. Curtis, *B. S. T. J. 12*, 76 (1933).
[29] G. E. Perreault, *Bell Labs. Record 10*, 412 (1932).
[30] H. A. Frederick, *B. S. T. J. 8*, 159 (1929).
[31] R. D. deKay, *Bell Labs. Record 16*, 236 (1938).

coils and transformers. In the moving coil microphone, the cylindrical coil moves axially in a slot between an inner magnetized cylinder and an outer magnetic cylinder which receives the radial flux threading the coil. For such a cylindrical coil in a uniform radial field, the e.m.f. is $-e = lB\frac{dx}{dt}$, where l is the total length of wire composing the coil, and x is its displacement perpendicular to the radial field. For a stationary coil linking a varying flux as in a transformer, $-e = AN\frac{dB}{dt} = AN\mu\frac{dH}{dt}$, where A and μ are the area and permeability of the core within which the magnetizing force is H. It is evident from these equations that high flux density or permeability are desirable, in order to yield the largest e.m.f. with least material.

4a. *Microphones, Magnetic Tape Recorders, Magnetos*

An application involving a moving coil is the public address microphone,[32] where the flux is established by means of a cobalt steel magnet, and is concentrated upon the moving coil by means of permendur pole-pieces.

An inverse application in which the coil is stationary and the magnet moves is the magnetic tape recorder.[33] In this, a steel tape which has been magnetized by speech currents is drawn between permalloy pole-pieces in pick-up coils. High coercive force, high signal-to-noise ratio, mechanical soundness, durability, and cheapness of the tape material are desirable.

The telephone magneto employs the e.m.f. generated by rotating a coil in a magnetic field. It has been constructed with iron armature and pole-pieces, and chrome steel field magnets. Recent designs using modern magnetic materials have indicated the possibility of large economies in volume.[34] The magnetic properties of available materials have now reduced the volume required by magnetic parts to a point where the major problem in magneto design is to compress the gears and shafts into correspondingly small space and yet maintain sufficient mechanical strength, durability, and convenience of operation.

4b. *Inductance Coils*

A very important application of induced e.m.f. focuses attention on the inductance of a coil of N turns surrounding a (closed) core of area A,

[32] R. N. Marshall & F. F. Romanow, *B. S. T. J. 15*, 405 (1936).
[33] C. N. Hickman, *B. S. T. J. 16*, 165 (1937).
[34] *Ericsson Bulletin No. 12*, 46 (1938).

magnetic path length l, and permeability μ. The inductance is increased through the presence of the core by an amount

$$L = 4\pi N^2 \mu A/l.$$

As noted earlier, when eddy current shielding is negligible such an inductance is accompanied at frequency f by hysteresis, residual, and eddy current resistances to give a total as follows:

$$R/L = \mu f(aB_m + c + ef).$$

At frequencies high enough to introduce eddy current shielding, the effective inductance due to a core of laminar thickness t and resistivity ρ is reduced below the ordinary inductance L_0 by the ratio

$$L/L_0 = \frac{1}{\theta}\frac{\sinh\theta + \sin\theta}{\cosh\theta + \cos\theta},$$

where $\theta = 2\pi t\sqrt{\mu_0 f/\rho}$. Figure 7 shows this ratio and the ratio $R_e/\omega L_0$ as functions of θ. As a practical example, the permeability of 6 mil (0.015 cm.) 4–79 Mo-permalloy is reduced to about 75 per cent of its initial value (22,000) at 1 kilocycle, and to about 17 per cent at 10 kc.

The telephone loading coil adds inductance to the telephone line, but it must not add excessive resistance. Furthermore, its inductance must be extremely stable with the lapse of time, and under severe operating conditions, such as occasional current surges induced from lightning discharges. Iron wire cores for loading coils were supplanted over twenty years ago by compressed iron powder cores, and these in turn gave way to permalloy powder cores. The latest improvement is the introduction of 2–81 Mo-permalloy powder cores.[7] The reduction in size of cores with these improvements is shown in Fig. 8.

Another method of loading a line is by sheathing the conductor with a continuous layer of magnetic material. This method was used with notable success on submarine telegraph cables by wrapping permalloy tape upon the conductor, and annealing before applying insulation.[3] The location of the loading material is shown in Fig. 9. The continuous loading of long submarine telephone cables has been shown to be feasible using thin 7.5–45 Mo-perminvar tape.[7]

Retardation and choke coils have a great variety of applications, running from a tiny coil weighing 3½ ounces [35] to a 4600 lb. generator ripple suppressor.[35] The contrast is evident in Fig. 10. Retardation

[35] D. W. Grant, *Bell Labs. Record 11*, 173 (1933).
[36] R. A. Shetzline, *Bell. Labs. Record 17*, 34 (1938).

coils, used as network elements, are generally equipped with compressed powder cores, and the same improvements are indicated as for loading coils noted above. Laminated permalloy cores are often used for low-frequency applications (ringing, telegraph), where high inductance is desired, and a-c. losses are naturally low.

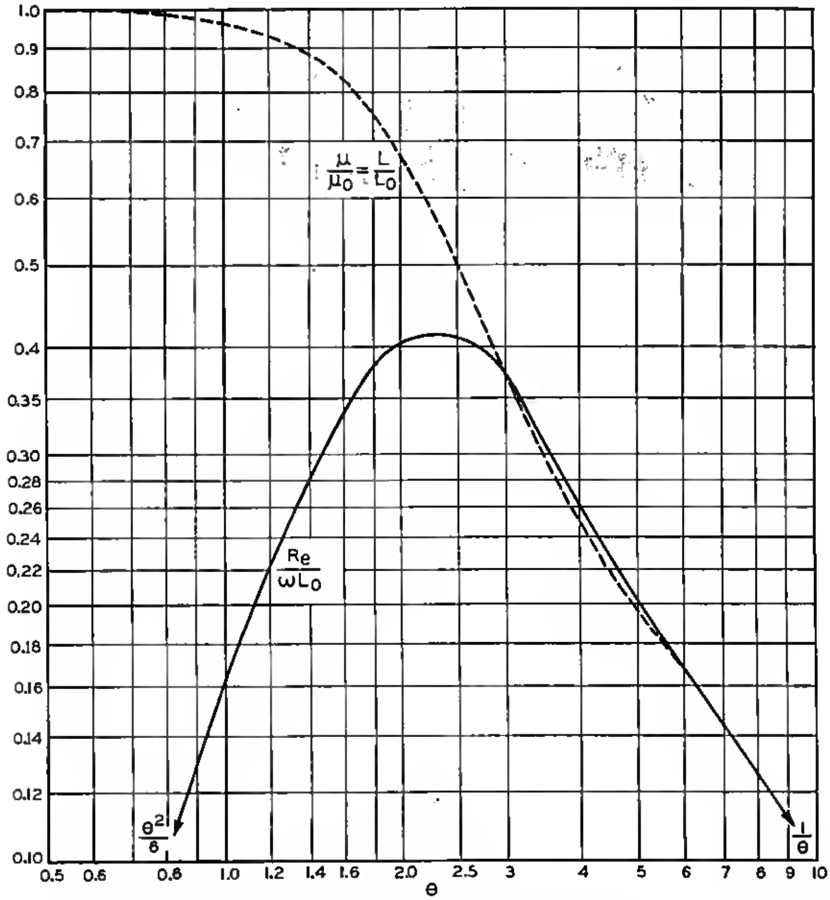

Fig. 7—Effect of eddy current shielding on apparent permeability and on eddy current resistance/reactance ratio of sheet core material.

Coils designed for direct currents must have cores with high a-c. permeability in the presence of superposed field, i.e. they must be made of high permeability magnetic materials having high saturation values. Reference to Fig. 5 shows permendur outstanding in this regard. In practice, the low costs of silicon iron or magnetic iron are

frequently decisive in the selection of these materials instead of the technically superior materials noted above. Air-gaps are often found necessary to reduce the superposed field strength in the magnetic core.

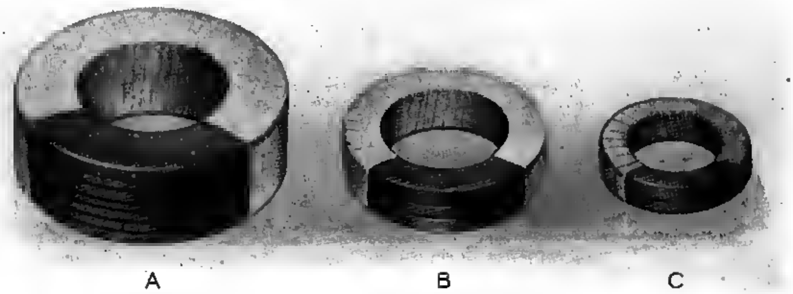

Fig. 8—Relative sizes of compressed powder cores for loading coils; *A*. Iron, *B*. 80-permalloy, *C*. 2–81 Mo-permalloy.

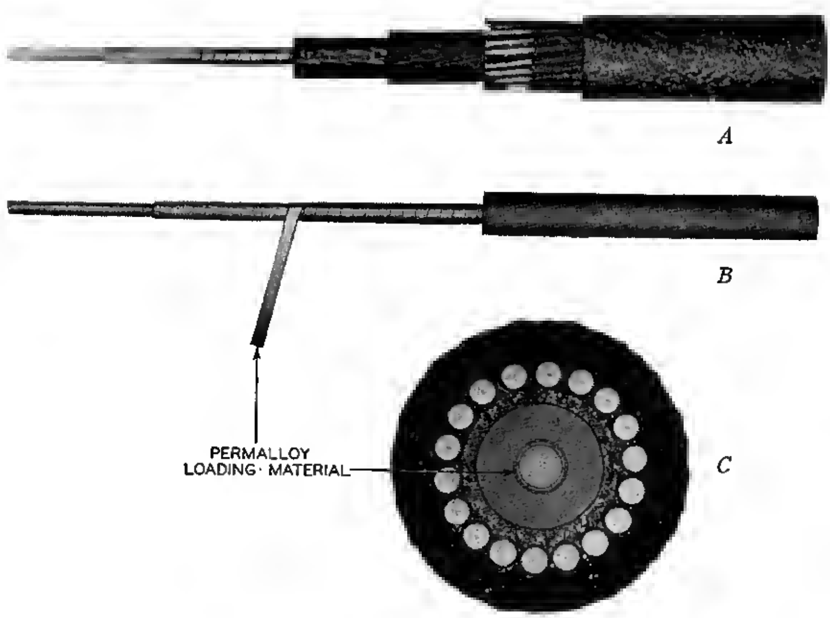

Fig. 9—Permalloy loaded telegraph cable; *A*. Armored deep sea type, *B*. Gutta percha insulated core, *C*. Enlarged cross sectional view.

This serves to retain a fairly large reversible permeability in the core, and, if the air gaps are not too large, it yields a larger net effective permeability than could be obtained without air-gaps.

A further type of inductance is the impulse coil used in harmonic generators.[37] The cores of these coils should be saturated over most of the magnetizing cycle, and reverse very quickly and completely just as the magnetizing force passes through zero. This implies use of material having a high permeability, and a high resistivity, such as 4–79 Mo-permalloy.

Fig. 10—Large and small coils used in the telephone system.

4c. *Transformers*

With transformers, the inductance and losses of the individual coils can be analyzed as simple inductances, for which the considerations of

[37] E. Peterson, J. M. Manley & L. R. Wrathall, *Elec. Engg. 56*, 995 (1937).

4b apply. In addition, however, the coupling factor between coils on the same core becomes of especial importance. In the usual design the flux linkage common to the primary and secondary is largely contained in the magnetic material, while the leakage flux is controlled by the reluctance of the air path. It is thus evident that a large value of core permeability is required to obtain a high coupling factor. Of course, advantages indicated by high permeability may be lost through improper design.

The earliest transformer employed in the telephone plant was the induction coil. This originally consisted of two windings on a core composed of a bundle of iron wires.[38] Later, silicon iron sheet cores were introduced.

Input and output transformers have varied applications for which special types of cores are required. Where superposed current is not involved, space and weight can be economized by use of high permeability materials such as chrome or molybdenum permalloy.[39] Eddy current shielding at higher frequencies will offset much of the permeability advantage indicated for these materials unless they are laminated sufficiently. However, thin laminations are costly to prepare and stack, and difficult to insulate and handle without mechanical injury and corresponding reduction of permeability. An intermediate thickness of permalloy sheet is generally chosen, which secures a considerable advantage in permeability over iron, without prohibitive cost.

Where a winding must carry direct current, conditions are similar to those applying to choke coils, and materials with high reversible permeability at high magnetizing forces are required. Frequently, for large magnetizing forces, it is desirable to include air-gaps in the magnetic circuit. Silicon iron is the ordinary material for such application, as it is for power transformers.

4d. *Magnetic Shielding*

A further application of induction effects is in magnetic shielding of apparatus. A magnetic shield consists of a high permeability shell (4–79 Mo-permalloy, or 78.5 permalloy) which shunts flux around the enclosed apparatus. For a-c. shielding, alternate layers of copper and permalloy sheet are very effective in magnetic shunting and eddy current screening of the enclosed space.[40] High initial permeability,

[38] Cf. p. 43 of Reference 26.
[39] A. G. Ganz & A. G. Laird, *Elec. Engg. 54*, 1367 (1935).
[40] W. G. Gustafson, *B. S. T. J. 17*, 416 (1938).

mechanical workability, and low cost are desirable for such applications.

5. *Magnetostriction*

The relative change in length of a magnetic bar upon magnetization, $\delta l/l$, ranges from negative to positive values, depending on alloy composition, and is roughly proportional to B^2. If a polarizing field is applied, small additional alternations of field will give accompanying and nearly proportional alternations of length of a bar. These alternations evidence themselves in the electrical constants of a coil enclosing the bar.

This effect can be utilized in oscillators and filters for frequencies which involve the use of mechanically resonating bars of convenient size. Among the high permeability materials, 45 permalloy appears to give the largest magnetostrictional effect.[41] In order to limit eddy current losses, the material must be laminated more or less finely, depending on the frequency.

The inverse magnetostriction effect by which e.m.f. is generated in a coil when the core is vibrated, becomes objectionable as a source of circuit noise in the transformers of high gain amplifiers.[39] An alloy with minimum magnetostriction such as 81 permalloy or 4–79 Mo-permalloy is preferred for such cases.

Other effects of magnetostriction are the generation of sound by the cores of coils subject to alternating magnetization, and the appearance of undesired resonance effects in the electrical circuit at frequencies at which the core resonates mechanically.

6. *Thermal Variation of Permeability*

The initial permeability of ordinary magnetic materials increases more or less slowly with increasing temperature, until a maximum value is reached, above which temperature the permeability declines very rapidly to the non-magnetic, or Curie point. The Curie point of an alloy can be moved down the temperature scale by adding non-magnetic materials, such as Mo, Cr, Cu, etc., to the alloy.[42]

The positive temperature coefficient of inductance of powder core coils due to thermal change of permeability becomes objectionable in crystal filters, where only very small variations in the resonant frequencies can be tolerated.[43] It is made slightly negative to counteract the small positive coefficient of mica condensers by the admixture with

[41] A. Schulze, *Zeit. f. Phys. 50*, 448 (1928).
[42] G. W. Elmen, *Bell Labs. Record 10*, 2 (1931).
[43] C. E. Lane, *B. S. T. J. 17*, 125 (1938).

the regular 2–81 Mo-permalloy powder of a small amount of permalloy powder containing about 12.5 per cent of molybdenum. The latter material has a Curie point just above room temperature.

Conclusion: Desirable and Possible Improvements

It appears from the above inspection of the magnetic elements of apparatus that there is a general desire for all properties which contribute to magnetic effects to be increased, and for those which cause apparatus energy losses to be decreased. A considerable success has already been achieved in these directions. The obstacles to further improvement are in part difficulties in commercial application of laboratory techniques, and in part ultimate limitations to the properties of materials.

The chart in Fig. 11 shows the recent trend toward the realization of the best possible magnetic properties in new materials or by improved processes. Values are given for the year 1920 (i.e. before commercial application of the permalloys), for 1939 as commercially and as experimentally realized, and for what may be considered as the attainable limit. It is evident that most of the properties which could be improved have been improved in commercial materials by a factor of ten or so within the last twenty years. A further improvement of several properties by a factor as large as ten has been observed by experimental procedures. These improvements have not been utilized in all cases, either because they may not be of great practical value, or because they involve processes which are commercially impracticable, or materials which are very expensive. Thus, the highest value of μ_m has been attained on a single crystal of H_2 purified iron [44] cut so as to make a hollow parallelogram with sides parallel to the (100) crystal axes, and annealed in H_2 below the α-γ transformation point. The highest permanent magnet quality has been attained with a platinum cobalt alloy [45] costing some $400 per pound.

One of the main objectives of commercial magnetics research has been the attainment of higher permeabilities—initial, maximum, reversible, and at high flux densities. The reversible permeability is closely linked with the initial permeability and saturation flux density. The permeability at high flux densities [46] appears to be susceptible to considerable increases by proper treatment of materials. The initial permeability can be increased by proper technique, but such gains are frequently sacrificed in practice because of unavoidable mechanical

[44] P. P. Cioffi & O. L. Boothby, *Phys. Rev. 55*, 673 (1939).
[45] W. Jellinghaus, *Zeit. Tech. Phys. 17*, 33 (1936).
[46] For example, at $B = 10{,}000$, or $B = 20{,}000$.

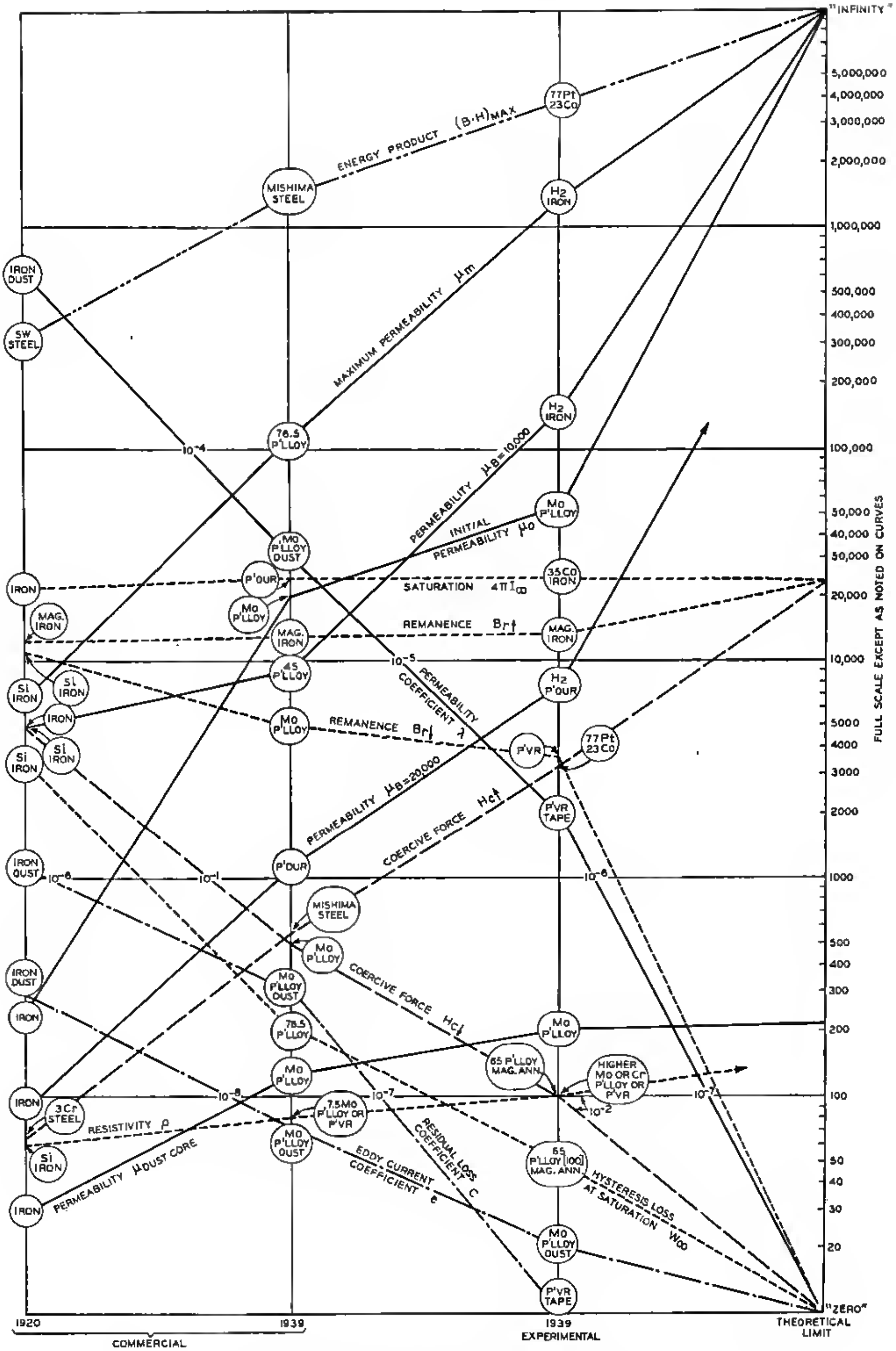

Fig. 11—Improvements in the properties of magnetic materials since 1920, in relation to theoretically possible properties.

stresses, or because of large eddy current shielding. Higher maximum permeabilities than now attainable do not promise great utility. However, the low values of coercive force and hysteresis loss found with materials having high maximum permeability may be sufficiently desirable, regardless of permeability needs.

Another important objective of magnetics research has been to reduce energy losses. Hysteresis loss at low flux densities, as indicated by the loop area coefficient a, should be decreased to cut down harmonic generation and modulation in magnetic core coils. Perminvar has shown desirably reduced losses, but it is sensitive to magnetic and mechanical conditions. Eddy currents are controlled by resistivity and degree of subdivision of the magnetic core. The resistivity of magnetic alloys can be increased to around 100 microhm-cms. by alloying with large enough quantities of chromium, molybdenum, etc., but at a serious sacrifice of magnetic quality for resistivities above about 60. Eddy current suppression by laminating or pulverizing the magnetic material thus offers a greater range of control than resistivity adjustment.

Permanent magnetic materials have also reached a very successful stage, from the magnetic point of view. The greatest handicap of the better materials is extreme hardness, which hampers fabricating processes.